THE ϕ MESON AND "CHIRAL-MASS-MESON" PRODUCTION IN HEAVY-ION COLLISIONS AS POTENTIAL PROBES OF QUARK-GLUON-PLASMA AND CHIRAL SYMMETRY TRANSITIONS

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ABSTRACT

Possibilities of observing abundances of ϕ mesons and narrow hadronic pairs, as results of QGP and Chiral transitions, are considered for nucleus-nucleus interactions. Kinematical requirements in forming close pairs are satisfied in K^+K^- decays of S(975) and δ(980) mesons with small P_T, and ϕ(1020) mesons with large P_T, and in $\pi\pi$ decays of familiar resonance mesons (ρ, ω, A_1, ...) only in a partially restored chiral symmetry. Gluon-gluon dominance in QGP can enhance ϕ meson production. High hadronization rates of primordial resonance mesons which form narrow hadronic pairs are not implausible. Past cosmic ray evidences of anomalous ϕ production and narrow pair abundances are considered.

1. Introduction. First (or second) order phase transitions have been demonstrated for Quark-Gluon-Plasma(QGP) and Chiral Symmetry Restoration in various lattice QCD calculations.[1] Phenomenological consequences of new states of matter have been discussed rigorously in the past few years. Some signatures which may discriminate new states from ordinary hadronic processes are considered for on-going and future experimental investigations: (i) direct photons and lepton-pairs;[2] (ii) large average P_T;[3] (iii) rapidity-azimuth fluctuations;[4] (iv) strangeness production;[5] (v) "fade-out" of resonance mass peaks.[6]

The first issue has been most quantitatively studied so far, but the results of calculations are found less prominent than initially expected.[7] The second item, large P_T, has been attracting some critical attentions, since there are some experimental indications in the JACEE cosmic ray data[8] and in S$\bar{p}$pS data,[9] which can be discussed as influences of hydrodynamical expansion[10] and thermodynamical manifestation[11] of plasmas. The third issue has been only naively conjectured,[12] but some expectations are made on the basis of super-cooling and deflagration.[13] The fourth issue, strangeness, has been emphasized by several people,[14] however, negative arguments against its abundant production are also raised recently (based on large entropy consumption in pions).[15] The last issue, being least studied to date, seems to be of particular interest, because it has been the only predicted diagnosis of Chiral transitions.

We examine other potential probes of new states of matter, considering several anomalous symptoms uniquely shown for nucleus-nucleus interactions in the past cosmic ray experiments. First, the possibility of abundant ϕ meson production in QGP is considered. Then, we shall study the possibility of observing reduced-mass resonance mesons in partial chiral symmetry.

2. ϕ Meson Abundance. Koshiba et al.[16] and Kim[17] observed multiple Kaons in nucleus-nucleus collision events in Brawley Stack emulsion. The former, particularly, have shown that the observed Kaons are mostly due to ϕ mesons which are identified by an invariant-mass study of two Kaons. This is,

however, inconceivable at first glance, because strong suppression of ϕ mesons has been established in elementary particle interactions. This suppression is best understood by (1) its large mass (1,020 MeV/c^2), (2) small coupling constant of s-quark, and (3) Okubo-Zweig-Iizuka (OZI) rule for disconnected quark diagrams (small mixing of $s\bar{s}$ with $u\bar{u}$ and $d\bar{d}$).

These fundamental suppressions do not seem quite obvious in nucleus-nucleus collisions for the following reasons: (1) large mass suppression in the Boltzman factor may not be valid among different flavors; primordial $s\bar{s}$ can be as many as $u\bar{u}$ and $d\bar{d}$ in QGP, as often stressed by Rafelski.[5] (2) a small coupling constant is not unique for s-quark at high temperature as QCD reduces strengths of light quark couplings. Even if not, their intrinsic difference is small. (3) The OZI suppression is effective to $q\bar{q} \rightarrow q\bar{q}$ process, but it is absent for stronger (more rapid) $gg \rightarrow q\bar{q}$ process. In a gluon-rich environments(QGP) $s\bar{s}$ production is dominated by the latter.

The ϕ/π ratio should be enhanced in QGP at least to the 1 % level, apart from well-known low values (< 0.1 %). If we follow Rafelski's calculation of $s\bar{s}$ abundance in QGP, and separately apply the Boltzman factor to strange particles, we get ϕ/π ratio upto 23 %. (The P_T distribution of them may be different as well, if hydrodynamical flow of QGP is strong. A universal P_T formula, $dN/dP_T \propto \exp(-m_T/T_0)$; T_0 = 170 MeV, may not be valid in universal CM system, but only in the rest system of the hydrodynamical front plane.) Such a high ϕ/π ratio, though possible, is not guaranteed only from above considerations. Particularly, an alteration of the universal Boltzman factor for different flavors remains too arbitrary.

On the other hand, the Koshiba data implies ϕ/π ratio 32 ± 17 % in the target fragmentation region. It is also interesting to note that K/π ratios for nucleus-nucleus and proton-nucleus events in the same data turned out to be 0.41 ± 0.15 and 0.17 ± 0.11, respectively.[21] This value is consistent with the latest Rafelski estimate[22] and the upper bound given by McLerran.[15] If we accept Kaon data of Koshiba et al., we are inevitably compelled to reconsider the strangeness suppression.

The ϕ meson is an unique particle in the sense that it does not decay ($\tau \simeq$ 20 fm/c) before leaving a "fireball", and its decay particles (K^+K^-) remain closely associated with each other. In this regard, it is interesting to note another cosmic ray data which showed pronounced narrow pairs in nucleus-nucleus collisions.[18,19] These data, if explained by ϕ mesons, require $P_T(\phi)$ more than 1.5 GeV/c (for pairs with Δy < 0.2 and $\Delta\phi < 30^o$).[23] S and δ mesons make "too narrow" K^+K^- pairs (Δy, $\Delta\phi \simeq 0$). The required high $\phi(P_T \gtrsim 1.5$ GeV/c)/π(all P_T) ratio (~ several %) to account for all the pair abundances is unacceptable by any means, which eliminates the candidacy of high P_T ϕ mesons for the observed pairs. Nevertheless, as discussed later, ϕ mesons and other familiar resonance mesons can make very narrow hadronic pairs without high P_T in partial chiral phase.

3. Mesons in Partial Chiral Symmetry. Chiral Symmetry Restoration is shown by many calculations to take place at almost the identical critical temperature (T_{ch}) as the deconfinement (QGP) transition (T_c). The consequence of the chiral symmetry at high temperature is the reduction of resonance masses. Chiral transition above Tch may not alter the main scenario of dynamical processes of nucleus-nucleus interactions, at least, that of hydrodynamical expansion of QGP. Nonetheless, an influence on the hadronization process must be considered, because the hadronization process is at the same time a process of dynamical symmetry breaking of chirality.

At temperature just below the QGP phase transition ($T \leq T_c$) when early hadronization starts, chiral symmetry breaking is incomplete. The mass of a resonance meson composed of u or d quarks is significantly light at high temperature, while those of π's and K's remain almost normal. Chiral counterparts, for example, $\rho((1^-)^-)$ and $A_1((1^+)^+)$, have different masses, 770 and 1,270 MeV/c^2, respectively in normal nuclear phase. Their mass difference vanishes above Tch. The mass formulae in the quark model gives a degree of symmetry breaking as a function of the temperature:[20]

$$m(T)/m_0|_{T\sim T_{ch}} \rightarrow 2.03\{(T_{ch} - T)/T_{ch}\}^{\frac{1}{2}}, \tag{1}$$

where m_0 represents the constituent quark mass (~ 300 MeV). Using a formula given by Pisarski,[20] we get ρ meson mass at different T. When Tch = 215 MeV and Tc = 207 MeV, for example, m_ρ increases rapidly with decreasing T:

$$m_\rho \simeq 290 \text{ MeV } (T = 206 \text{ MeV}),\ 341 \text{ MeV } (T = 205 \text{ MeV}),\ \cdots . \tag{2}$$

The decay Pmax values for $\rho(T = 206, 205 \text{ MeV}) \rightarrow \pi\pi$ are only 63 MeV and 96 MeV, respectively, which can explain observed narrow pairs ($dN/d(\Delta\phi)$ for $\Delta y \leq 0.2$) satisfactorily without assuming high P_T.[23] Other resonance mesons are similarly lighter than their ordinary values in normal nuclear phase.

The number of primordial $q\bar{q}$ mesons can be evaluated by the combination rate at unit space-time,

$$A \equiv \frac{dN}{dt\ dx^3} = (1/2) \int_{4m^2}^{\infty} s ds \cdot \delta(s - (k_1 + k_2)^2) \int \frac{d^3k_1}{(2\pi)^3|k_1|} \int \frac{d^3k_2}{(2\pi)^3|k_2|}$$
$$\times \{C_g f_g(k_1) f_g(k_2) \bar{\sigma}_{gg\rightarrow q\bar{q}}(s) + C_q f_q(k_1) f_q(k_2) \bar{\sigma}_{q\bar{q}\rightarrow q\bar{q}}(s)\}, \tag{3}$$

where C_g and C_q are determined by the number of degrees of freedom for gluons and quarks, and $\bar{\sigma}(s)$'s are cross sections for gluons and quarks to form a specific $q\bar{q}$ state. The ratio of ($q\bar{q}$) states frozen out in the temperature intervals Tc - T and Tc - T_f can be estimated by

$$R(T) \equiv \int_T^{T_c} dT \cdot A(T) \int_\Omega d^4x\ \delta(T - T(x)) / \int_{T_f}^{T_c} dT \cdot A(T) \int_\Omega d^4x\ \delta(T - T(x))$$
$$\simeq \{(T_c/T)^6 - 1\}/\{(T_c/T_f)^6 - 1\}, \tag{4}$$

where $T_c > T > T_f$, with T_f being a final temperature ($T_f = T_0 \simeq 170$ MeV). When we consider R at T = 205 MeV, about 3 % of all final states are shared by primordial mesons in the earliest chiral breaking phase. Though the evaluation is crude (neglecting many dynamical factors), it is interesting to note that "chiral mesons" are not negligible in discussing the final state pair correlation. A question still remains how ππ's from chiral mesons can survive during meson-meson final state interactions. We tentatively neglect this, as the decay width Γ is proportional to $\{(T_c - T)/T_c\}^{3/4}$,[20] and the lifetime of "chiral ρ meson" is correspondingly long (several fm/c).

Chiral symmetry does not affect s-quark mesons very much. Nevertheless, a few times 10 MeV mass reduction is not unreasonable for ϕ mesons. This permits primordial ϕ mesons decay into narrow K^+K^- pairs even with small P_T.

The above discussions are highly speculative, as many assumptions are left unjustified. However, the hadronization mechanism from QGP, particularly from chiral symmetry, seems to have potential sources of narrow pairs.

<u>4. Conclusions.</u> The ϕ meson abundance in nucleus-nucleus interactions can be much higher ($\phi/\pi \geq 1$ %) than that in proton-proton collisions (ϕ/π < 0.1 %). The highest possible value in QGP may be 23 %, though this is too optimistic. Some cosmic ray data suggest much higher values ($\phi/\pi \simeq 30$ %) in a narrow target fragmentation region. It is too high for a plausible

explanation without assuming some strangeness abundances in cosmic ray heavy-ion events. Though inspiring, the observed data are limited to only several events (E > 1 TeV/amu). Follow-up experiments are required to consider new states of matter for them.

The hadronic narrow pairs might involve decay products of "chirally symmetric primordial mesons" (bound state of $q\bar{q}$: cf. Cooper-pair, i.e. phonon). However, the existing pair correlation data might be mostly accounted by some unclarified experimental errors and by more conventional mechanism such as the HBT effect.[19] Further studies may be required for confirming non-trivial pair abundances in the existing data. We do not consider at present any direct relationship of the experimental data to the above described scenario, though tempting, because both studies are still very primitive. Experimentally, measurements of $\langle P_T \rangle$ and invariant mass of a pair (with identity of the particle species) are possible in the backward hemisphere within nuclear emulsion techniques. If these data become available, the study of pairs will be more interesting. However, pair observations have some difficulties to deal with very high multiplicity/high energy density events; too high a particle density obscures any meaningful narrow-pair correlations. (Rapidity densities for the study of pair abundances may be limited to, probably, $dN/dy \sim 100$.) In this sense, light nuclei collisions and/or intermediate impact parameter events at high energy would best suit for observations, but with a risk to fall short of energy densities for the phase change. Theoretical developments for early hadronization processes are important in confirming the suggested scenario of (chiral transition → primordial "chiral mesons" → narrow hadronic pairs).

No definitive judgements for existing data are possible at this stage, however, we conclude that these kinds of observations can be potential probes of QGP and Chiral Symmetry Restoration when new states of matter are actually realized in high energy nucleus-nucleus collisions with moderate rapidity densities.

5. Acknowledgements. The authors acknowledge discussions with Drs. O. Miyamura, T. A. Parnell, and T. Tabuki.

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